

Semi-elastic cross section for a scalar resonance of mass 750 GeV

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Abstract

We assume that the recently reported excess over Standard Model expectations in the diphoton production is originated from a new scalar boson ϕ which interacts with photons through the coupling $\propto \phi F^2$. We obtain the cross section for semi-elastic production process $pp \rightarrow p\gamma p \rightarrow p\phi qX$ by considering $\phi\gamma\gamma$ and $\phi\gamma Z$ couplings and discuss the constraints on the coupling parameters. We investigate the potential of the semi-elastic production process to probe $\phi\gamma\gamma$ and $\phi\gamma Z$.

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I. INTRODUCTION

Recently a new resonance of mass around 750 GeV has been reported by the ATLAS and CMS Collaborations [1, 2]. Although it is not confirmed with a significant statistics, we may expect that it is a genuine signal coming from new physics beyond the Standard Model. We assume that the signal is real and caused by a new neutral scalar boson ϕ which interacts with gauge bosons. We will ignore its coupling to gluons and quarks since no evidence for resonant particles is observed up to now in the dijet final state [3]. The new scalar resonance can be investigated in a model-independent way by means of the effective Lagrangian formalism. In writing effective interactions of ϕ with gauge bosons we employ the formalism presented in Refs.[4, 5]. The effective Lagrangian which describes $\phi\gamma\gamma$ and $\phi\gamma Z$ couplings is given by

$$\mathcal{L} = c_{\gamma\gamma}\phi F^{\mu\nu}F_{\mu\nu} + c_{\gamma Z}\phi F^{\mu\nu}Z_{\mu\nu} \quad (1)$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$. Here, A and Z are photon and Z boson fields. The coupling constants $c_{\gamma\gamma}$ and $c_{\gamma Z}$ have the dimension of inverse energy. They are related to the coefficients of the effective operators before the symmetry breaking through $c_{\gamma\gamma} = \cos^2\theta_W f_B^{-1} + \sin^2\theta_W f_W^{-1}$ and $c_{\gamma Z} = 2\sin\theta_W \cos\theta_W (f_W^{-1} - f_B^{-1})$ [4, 5].

The origin of this new resonance has been discussed in a vast number of studies in the literature. These studies cover a wide range of new physics scenarios such as string inspired models, gauge symmetry models, radiative and top seesaw models, Next-to-Minimal Supersymmetric Standard Model, model independent analysis via effective lagrangian, etc.[5–9]. The production of the scalar resonance has been investigated in elastic proton-proton scattering in Refs.[5–8]. In Refs.[5, 8] authors also considered inelastic photon-photon fusion and took into account of the effective couplings $\phi\gamma\gamma$, ϕZZ , $\phi Z\gamma$ and ϕWW . In this paper we will consider the semi-elastic production of the scalar boson ϕ via the process $pp \rightarrow p\gamma p \rightarrow p\phi qX$. Some part of the cross section in the photon-photon fusion should belong to semi-elastic processes. It is therefore important to know the size of the cross section for semi-elastic production of the scalar boson. Furthermore, with the aid of forward detectors semi-elastic processes can be efficiently discerned from inelastic processes. They can be considered in isolation from inelastic processes and can be used to perform precision measurements. Therefore it is important to discover the potential of the semi-elastic production processes to probe ϕ couplings to Standard Model fields.

II. CROSS SECTIONS AND NUMERICAL RESULTS

In an elastic proton-proton scattering incoming protons do not dissociate into partons but they remains intact. On the other hand, in a semi-elastic proton-proton scattering, one of the incoming proton dissociates into partons but the other proton remains intact [10, 11]. Fig.1 represents elastic and semi-elastic production of the scalar boson in a photon-photon fusion. The elastic photon emission from the proton can be described by equivalent photon approximation. In equivalent photon approximation we employ the formalism presented in Refs.[12–14] where the electromagnetic form factors of the proton are taken into consideration.

The process $pp \rightarrow p\gamma p \rightarrow p\phi qX$ comprise of the subprocesses $\gamma q \rightarrow \phi q$ where q can be u, d, s, c, b quarks or anti-quarks. This gives totally 10 independent subprocess. Each of the subprocesses is described by t-channel γ and Z exchange diagrams (Fig.2). Hence both photon-photon and photon-Z boson fusion contribute to the ϕ production. The cross section for semi-elastic production $pp \rightarrow p\gamma p \rightarrow p\phi qX$ can be obtained through the integration

$$\sigma(pp \rightarrow p\gamma p \rightarrow p\phi qX) = \sum_q \int_{\xi_{min}}^{\xi_{max}} dx_1 \int_0^1 dx_2 \left(\frac{dN_\gamma}{dx_1} \right) \left(\frac{dN_q}{dx_2} \right) \hat{\sigma}_{\gamma q \rightarrow \phi q}(\hat{s}). \quad (2)$$

Here, $\frac{dN_\gamma}{dx_1}$ is the equivalent photon spectrum. Its analytical expression was defined in Refs.[12–15]. $\frac{dN_q}{dx_2}$ is the quark distribution function of the proton. We evaluate it numerically by using a code MSTW2008 [16]. x_1 represents the fraction E_γ/E where E_γ and E are the energy of the emitted photon and the proton. x_2 is the momentum fraction of the proton's momentum carried by the quark. The limits of the dx_1 integration is determined by the upper and lower bounds of the parameter ξ which represents the momentum fraction loss of the proton. After elastic photon emission protons generally deviate slightly from the direction of beam pipe and escape from the central detectors without interacting. Forward detectors can detect these intact scattered protons. The acceptance of the forward detectors is determined by the interval $\xi_{min} < \xi < \xi_{max}$. The use of forward detectors is especially necessary for high-luminosity runs at the LHC in order to isolate elastic or semi-elastic processes [17–20]. We will consider two different cases: In the first case we do not assume the existence of the forward detectors and take account of the whole interval $0 < x_1 < 1 - \frac{m_p}{E}$ for the dx_1 integration. This case makes sense if we want to examine the size of the cross section coming from semi-elastic processes to the whole production but do not intend to isolate the

semi-elastic production. In the second case we consider a forward detector acceptance of $0.015 < \xi < 0.15$ [21–24].

Experimental results indicate that this new resonance has a total width of $\Gamma_{total} \approx 45 \text{ GeV}$ and the observed number of events corresponds to $\sigma(pp \rightarrow \phi X)BR(\phi \rightarrow \gamma\gamma) \approx 3 - 6 \text{ fb}$ [1, 2]. Here the branching ratio is given by $BR(\phi \rightarrow \gamma\gamma) = \frac{c_{\gamma\gamma}^2 m_\phi^3}{4\pi\Gamma_{total}}$. To give an idea about size of the cross section coming from semi-elastic production we solve the equation $\sigma(pp \rightarrow p\gamma p \rightarrow p\phi q X)BR(\phi \rightarrow \gamma\gamma) = 5 \text{ fb}$ numerically for the couplings $c_{\gamma\gamma}$ and $c_{\gamma z}$. Corresponding plots are presented in Fig.3. In the figure the area restricted by the lines corresponds to the values of the total cross section less than 5 fb . Therefore the cross section for semi-elastic production of the scalar boson allows the values of $c_{\gamma\gamma}$ and $c_{\gamma z}$ within this restricted area. In Figs.4 and 5 we plot the total cross section of $pp \rightarrow p\gamma p \rightarrow p\phi q X$ as a function of the couplings $c_{\gamma z}$ and $c_{\gamma\gamma}$ for the LHC center-of-mass energies of $\sqrt{s} = 13 \text{ TeV}$ and 14 TeV . In Fig.4 we consider the whole interval $0 < x_1 < 1 - \frac{m_p}{E}$ for the dx_1 integration in Eq.(2). But in Fig.5 we consider the forward detector acceptance of $0.015 < \xi < 0.15$. We observe from these figures that the cross section for the acceptance of $0.015 < \xi < 0.15$ is approximately a factor of 1.5 smaller than the cross section for $0 < x_1 < 1 - \frac{m_p}{E}$.

In order to investigate the potential of the process $pp \rightarrow p\gamma p \rightarrow p\phi q X$ to probe $\phi\gamma\gamma$ and $\phi\gamma Z$ couplings in a future experiment we have performed a statistical analysis using a Poisson distribution. The expected number of events has been calculated through the formula $N = \sigma(pp \rightarrow p\gamma p \rightarrow p\phi q X)BR(\phi \rightarrow \gamma\gamma)L_{int}$ where L_{int} is the integrated luminosity. We assume that the number of observed events N_{obs} equal to the Standard Model prediction. The determination of an on-shell scalar boson with mass $m_\phi \approx 750 \text{ GeV}$ requires an invariant mass measurement of the final state photon pair. Therefore, a cut of $M_{\gamma\gamma} \approx 750 \text{ GeV}$ should be imposed on the invariant mass of final state photons. This cut reduces the contribution coming from background processes. Hence we ignore any background contribution and assume that $N_{obs} = 0$. This gives an upper limit of $N_{up} = 3$ for number of events at 95% confidence level. In Fig.6 we show 95% confidence level sensitivity bounds on the parameter space $c_{\gamma\gamma} - c_{\gamma z}$ for integrated luminosities of $L_{int} = 10, 30, 100$ and 200 fb^{-1} and forward detector acceptance of $0.015 < \xi < 0.15$. The center-of-mass energy of the colliding protons is taken to be $\sqrt{s} = 13 \text{ TeV}$. We have also calculated the bounds for center-of-mass energy of $\sqrt{s} = 14 \text{ TeV}$. We do not present the bounds for $\sqrt{s} = 14 \text{ TeV}$ since the bounds for $\sqrt{s} = 14 \text{ TeV}$ are very close to the bounds for $\sqrt{s} = 13 \text{ TeV}$. The difference between the

bounds for these two different center-of-mass energies does not exceed 2%.

III. CONCLUSIONS

The inelastic production of the scalar boson receive contributions both from $\gamma\gamma$, ZZ , $Z\gamma$ and WW fusion due to effective $\phi\gamma\gamma$, ϕZZ , $\phi Z\gamma$ and ϕWW couplings. On the other hand, the semi-elastic production $pp \rightarrow p\gamma p \rightarrow p\phi qX$ receives contributions only from $\gamma\gamma$ and γZ fusion and give us the opportunity to probe $\phi\gamma\gamma$ and $\phi Z\gamma$ couplings independent from ϕZZ and ϕWW . Another advantage of the semi-elastic production is that it provides a rather clean channel compared to inelastic production due to the absence of one of the incoming proton remnants. Moreover, in principle forward detectors can detect the momentum loss of intact scattered protons. The knowledge obtained in this way may be useful in reconstructing the kinematics of the subprocesses. Hence, the semi-elastic production $pp \rightarrow p\gamma p \rightarrow p\phi qX$ process can be considered as a candidate for precision measurements. It is obvious that the production of ϕ via elastic proton-proton scattering provides the most clean channel due to the absence of the remnants of both proton beams. But the elastic production has a lower energy reach and effective luminosity with respect to semi-elastic production.

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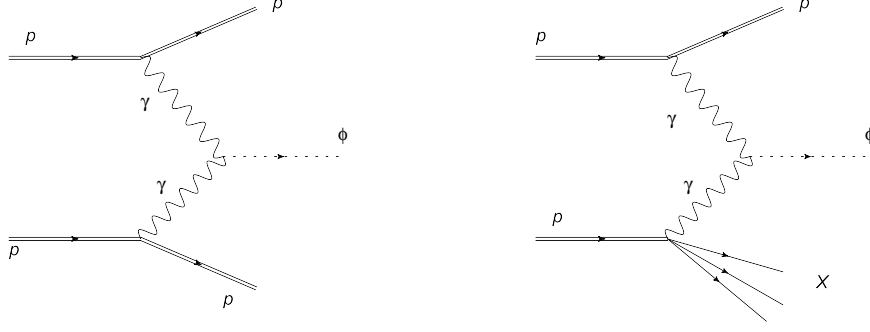


FIG. 1: Schematic diagram for elastic (left panel) and semi-elastic (right panel) production of the scalar boson in a photon-photon fusion.

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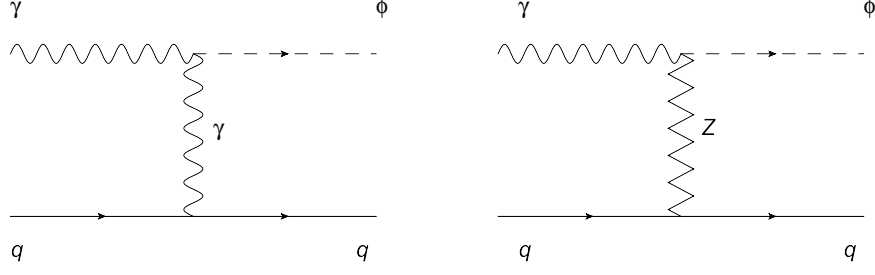


FIG. 2: Tree-level Feynman diagrams for the subprocess $\gamma q \rightarrow \phi q$.

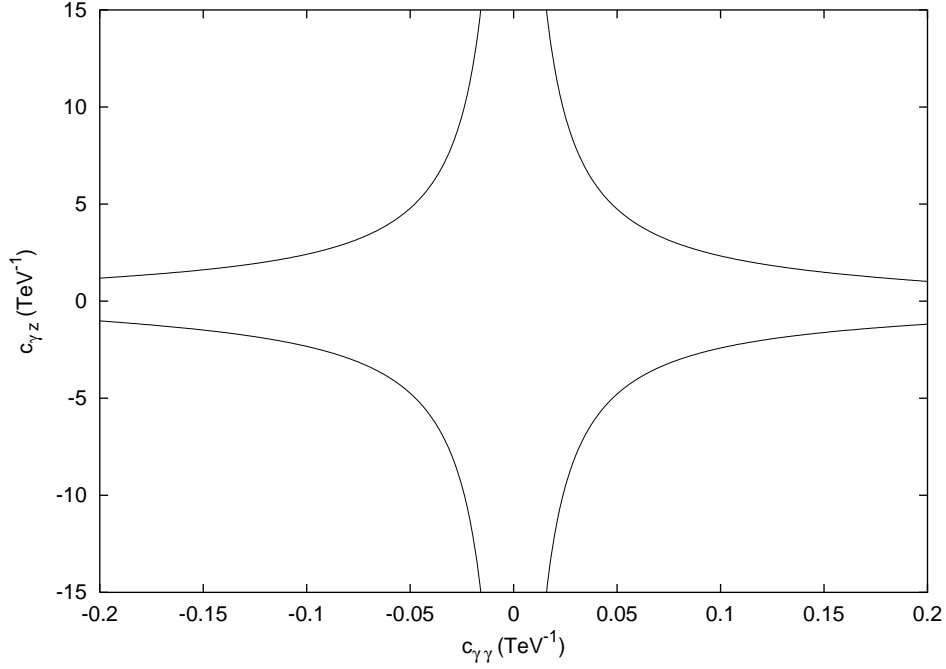


FIG. 3: The area restricted by the lines corresponds to the values of the total cross section $\sigma(pp \rightarrow p\gamma p \rightarrow p\phi q X) BR(\phi \rightarrow \gamma\gamma) \leq 5 \text{ fb}$. We sum all contributions from subprocesses $\gamma q \rightarrow \phi q$ for $q = u, d, s, c, b, \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 13 \text{ TeV}$. We consider the whole interval $0 < x_1 < 1 - \frac{m_p}{E}$.

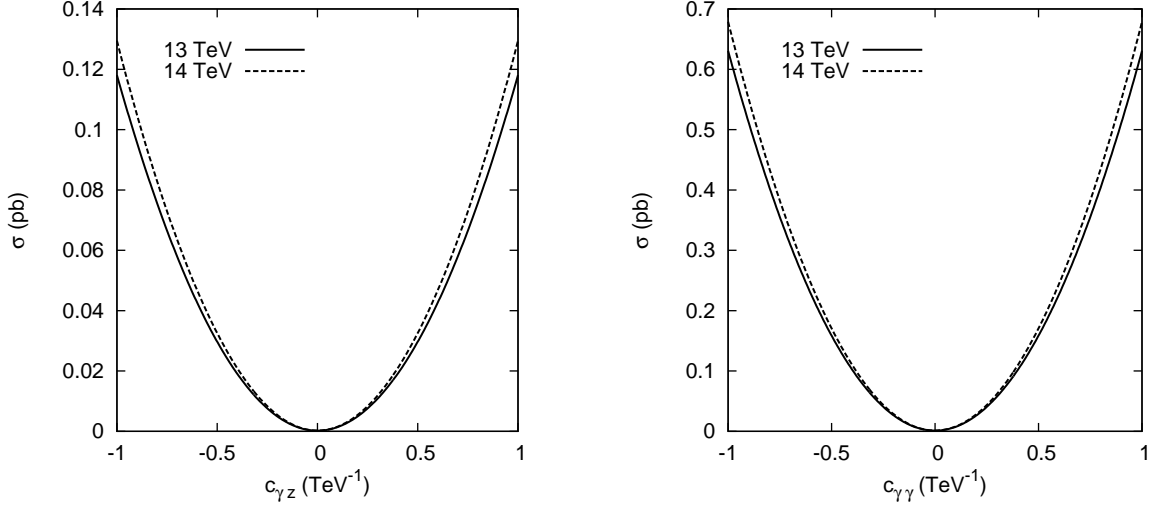


FIG. 4: Total cross section of $pp \rightarrow p\gamma p \rightarrow p\phi q X$ as a function of the coupling $c_{\gamma z}$ (left panel) and $c_{\gamma\gamma}$ (right panel) for two different LHC center-of-mass energies stated on the figures. We sum all contributions from subprocesses $\gamma q \rightarrow \phi q$ for $q = u, d, s, c, b, \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$ and consider the whole interval $0 < x_1 < 1 - \frac{m_p}{E}$. Each time only one of the coupling parameters have been kept different from zero.

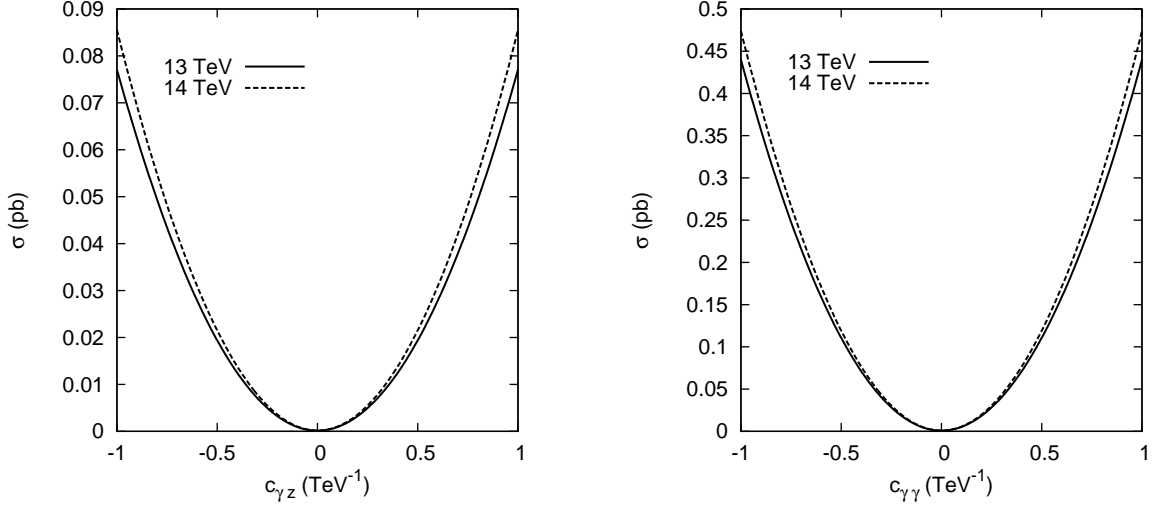


FIG. 5: Total cross section of $pp \rightarrow p\gamma p \rightarrow p\phi qX$ as a function of the coupling $c_{\gamma z}$ (left panel) and $c_{\gamma\gamma}$ (right panel) for two different LHC center-of-mass energies stated on the figures. We sum all contributions from subprocesses $\gamma q \rightarrow \phi q$ for $q = u, d, s, c, b, \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$ and consider the forward detector acceptance of $0.015 < \xi < 0.15$. Each time only one of the coupling parameters have been kept different from zero.

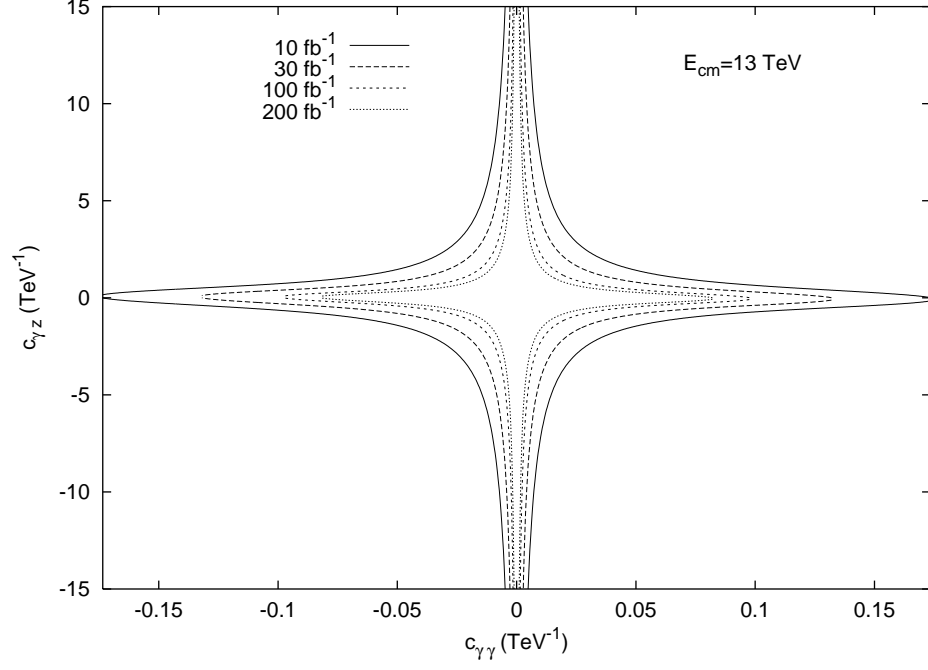


FIG. 6: The areas restricted by the lines represent 95% confidence level sensitivity bounds on the parameter space $c_{\gamma\gamma} - c_{\gamma z}$. The legends are for various LHC luminosities. The center-of-mass energy of the colliding protons is taken to be $\sqrt{s} = 13 \text{ TeV}$.